

Flux Mooring for the North Pacific's Western Boundary Current: Kuroshio Extension Observatory (KEO)

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PROJECT SUMMARY

Overview

As a NOAA contribution to the global network of Ocean Sustained Interdisciplinary Timeseries Environmental Observatory (OceanSITES) timeseries reference stations, an air-sea flux buoy, referred to as the Kuroshio Extension Observatory (KEO), was deployed in the Kuroshio recirculation gyre at 144.5°E, 32.3°N in June 2004. In June 2005, KEO was enhanced with a pCO₂ system to monitor carbon flux and additional subsurface instrumentation. The site is within the study domain of the 2-year (June 2004 - June 2006) NSF-funded Kuroshio Extension System Study (KESS) and KEO data are being combined with KESS measurements to evaluate processes affecting the heat content, Subtropical Mode Water formation, and recirculation gyre strength. For KEO's first three deployments, KESS provided shiptime, equipment and personnel for mooring operations. Collaborations with Japanese colleagues have begun and a formal partnership between JAMSTEC and PMEL is being developed. In February 2007, JAMSTEC IORGC in partnership with NOAA PMEL will deploy a KEO mooring (J-KEO) north of the Kuroshio Extension jet. For FY07, we plan to do KEO repairs and the mooring turnaround on Japanese research vessels. With the success of the KEO time series reference site, PMEL has been approached by several other potential partners. In particular, as part of a NSF-funded Carbon and Water Cycle project led by biogeochemical scientists from the University of Washington, in June 2007 PMEL will deploy a KEO-type air-sea flux mooring at the Ocean Weather Station PAPA in the Northeast Pacific. The PAPA and J-KEO offshoots of KEO represent a major expansion of the OceanSITES array. However, longterm funding for the PAPA air-sea flux mooring still needs to be secured to continue the PAPA mooring past the planned final recovery in August 2009. For more details on the KEO project and to access the realtime and delay mode data, see the KEO project website:

<http://www.pmel.noaa.gov/keo/>

Scientific Rationale

The Kuroshio, the North Pacific's poleward flowing western boundary current, separates from the coast near 35°N and becomes an eastward flowing jet, the Kuroshio Extension (KE). The KE represents the entrance region of the Pacific storm track and is characterized by some of the largest air-sea fluxes found in the entire North Pacific. It is one of the largest sinks of carbon in the North Pacific and has the characteristic maxima lobes of latent, sensible, and net surface heat loss. The net surface heat loss is particularly large during winter when the zenith angle of solar radiation is low and cold, dry continental air blows across the warm KE waters. Wintertime net surface heat losses average 330 W/m², and instantaneous fluxes can be much higher (Fig. 1).

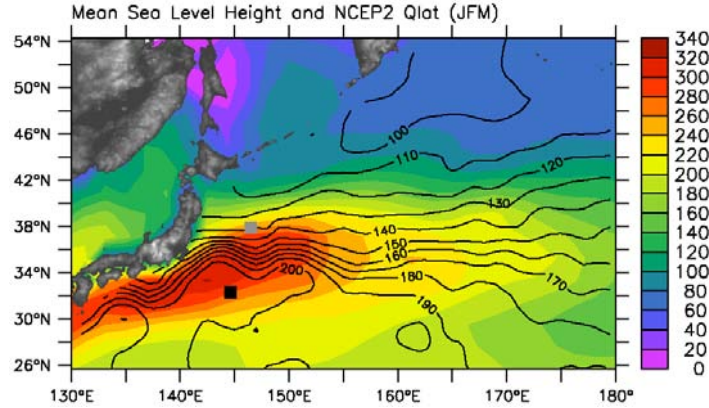


Fig 1. Climatological wintertime (January-March) latent heat flux and sea level height in the Kuroshio Extension region. The KEO site is indicated by a black square. The J-KEO site is indicated by a grey square.

The KE atmosphere-ocean system represents a major branch of the global heat cycle, whereby the input of excess heat at the top of the atmosphere in the tropics is carried poleward by a combination of the oceanic and atmospheric circulations (e.g., Trenberth and Caron 2001). In the subtropical North Pacific, a significant fraction of this heat is transported poleward by the Kuroshio. At the KE, heat is transferred from the ocean to the atmosphere. North of the KE, more heat is carried poleward by the atmosphere (in large part through transient eddies, i.e., storms) than by the ocean. Since the partitioning of the meridional heat flux between the atmosphere and ocean is closely related to KE air-sea interactions, fluctuations in the latter are surmised to impact the climate variability of the North Pacific basin.

As with the Gulf Stream in the North Atlantic, the KE is highly variable, featuring large-amplitude meanders that can pinch off to form anti-cyclonic warm-core eddies north of the jet and cyclonic cold-core eddies south of the jet. It carries 140 million cubic meters (140 Sv) of warm water eastward into the North Pacific. Wind driven Sverdrup transport accounts for about a third of this transport; the other 90 Sv is due to a tight anticyclonic recirculation gyre south of the jet whose size varies on seasonal-decadal time scales. At the center of the recirculation gyre, the thermocline is deep. During spring and summertime, a seasonal mixed layer can form. Wintertime convection erodes this stratification producing a thick (up to 400 m thick) isothermal $\sim 17^{\circ}\text{C}$ surface layer, termed *Subtropical Mode Water* (STMW). The STMW acts as a reservoir of heat. After it is isolated beneath the seasonal thermocline, it retains its water mass characteristics, reemerging the following winter to once again interact with the atmosphere. Through this “re-emergence mechanism”, mode water formed in a given winter is expected to affect SST in the subsequent fall and winter. Mode water formation is also associated with the sequestering of carbon. Large dust clouds blowing eastward off Asia are visible in satellite images and can be traced all the way across the Pacific basin. Asian dust is rich in iron and other nutrients. With the KEO carbon flux system, we hope to monitor whether the carbon cycle’s biological pump is affected by the passage of these clouds.

With surface currents of 3 knots (~ 150 cm/s) or more, a typically rough sea state, and lying in the Jet Stream’s storm track, the KE is an extremely difficult region to observe. Ships have been the traditional platform for observing air-sea interaction in western boundary currents. However, research cruises typically last no more than a month or two, and measurements from research ships

and vessels of opportunity are biased towards good weather. With the successful first year deployment, the instrumentation of the KEO mooring was expanded to include a carbon flux system and additional subsurface sensors as described below in Section 2. The KEO mooring is serving a wide community of climate sciences both in the US and in Japan. It is being used as a reference time series for comparison with numerical weather prediction products as well as satellite products (Kubota et al. 2006). It is also expected to provide new insights into the air-sea interactions within this climatically important region.

The KEO buoy is a contribution to the network of Ocean Reference Stations in a key region for air-sea interaction and therefore directly addresses the sixth element of the Program Plan for *Building a Sustained Ocean Observing System for Climate* (Ocean Reference Stations). This mooring also carries a Carbon Flux sensor to directly address the seventh element “Ocean Carbon Networks”. The KEO site has been endorsed by the International Time Series Science Team (co-chaired by R. Weller), which reports to the Ocean Observations Panel for Climate (OOPC). The two primary international ocean carbon research programs are the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and the Surface Ocean Lower Atmosphere (SOLAS) programs. Both groups strongly recommend carbon time-series measurements and are very supportive of NOAA’s efforts to develop a global pCO₂ mooring network. The KEO mooring is an important part of that effort. Time-series carbon measurements are also a key element of the United States research programs like the Ocean Carbon and Climate Change Program (OCCC).

The KEO mooring is operated by the NOAA Pacific Marine Environmental Laboratory and has several strong partners. The KEO buoy is an element of the OceanSITES network of reference sites and therefore is partners with other buoy programs in the network (e.g. STRATUS, NTAS, HOT, TAO/TRITON). Because KEO carries a carbon flux system, the KEO project also is a partner to the Global Carbon Cycle Program. This partnership is represented by co-PI Sabine. TAO and the NSF-funded Kuroshio Extension System Study (KESS) are particularly close working partners. The buoy was originally purchased under the now-complete NOAA OGP funded TAO-Eastern Pacific Investigation of Climate (EPIC) project. Professional staff supported by the KEO project are drawn from the pool of professional staff that participate in the TAO program. Located within the KESS array and within 10 km of N. Hogg and S. Jayne’s subsurface profiler mooring, the KEO buoy is contributing scientifically to the KESS experiment. KESS in turn has provided ship time, technicians and equipment for mooring operations. After the final KESS recovery cruise in June 2006, ship time will be provided through JAMSTEC. Drs. Ichikawa, Konda, and Tanimoto have developed a plan to deploy a surface buoy, much like KEO, north of the jet. This buoy (J-KEO) will be deployed in February 2007 through partnership with PMEL. Because KEO carries a carbon flux system, the KEO project also is a partner to NOAA’s Global Carbon Cycle Program. This partnership is represented by co-PI Sabine.

FY2006 ACCOMPLISHMENTS

The KEO project has 3 broad deliverables, each described below.

Deliverable 1: Calibrated surface meteorological and subsurface temperature, salinity and currents at the KEO site in the Kuroshio Extension recirculation gyre at 32.3N, 144.5E.

The KEO mooring diagram is shown in Fig 2. Operation of the KEO mooring requires refreshing the system at least once a year, pre- and post-calibrating all sensors, processing realtime data and making it available in near-realtime through the KEO website, processing delay-mode high resolution data and making it available with 6 months through the KEO website.

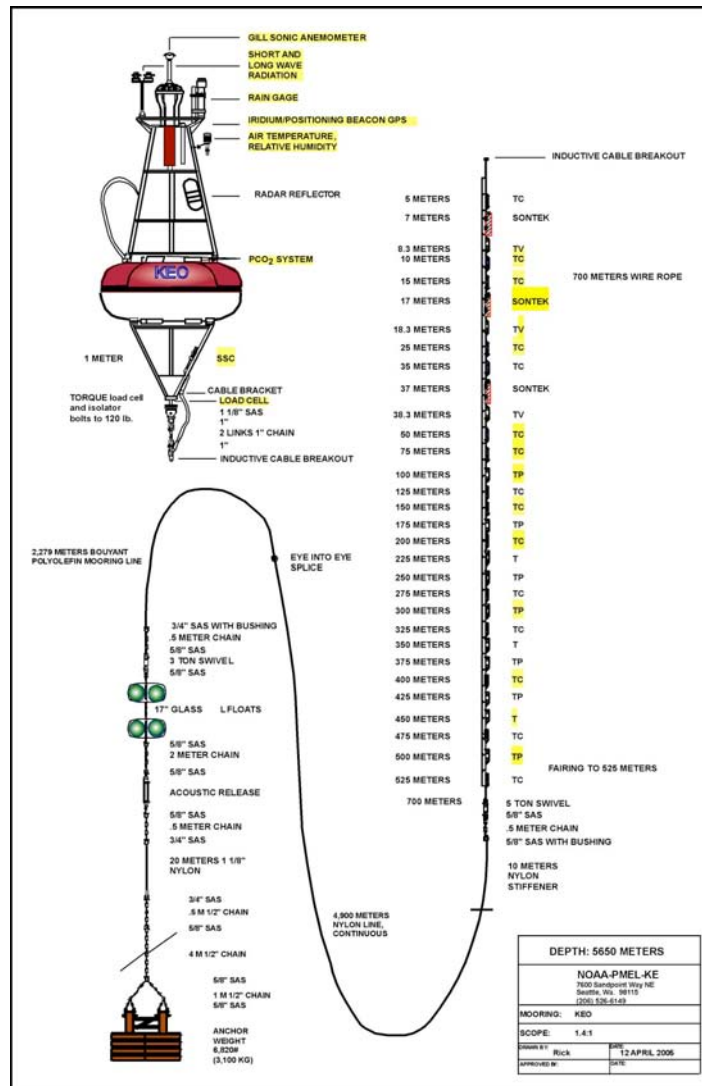


Fig. 2. KEO diagram. Telemetered measurements are highlighted in yellow.

On November 6, 2005, the buoy and the line with all of the subsurface sensors broke away from its anchor and began drifting southeastward. Since the buoy position is monitored on a daily basis, we were able to make immediate arrangements for a rescue. As luck would have it, Dr. Ichikawa had just left port on the R/V Kaiyo. Within 3 days, he had recovered the KEO buoy and all of the subsurface sensors. The equipment recovered was valued at more than \$150,000. However, perhaps more important, since the high resolution data are stored in the subsurface modules and the surface electronics “tube”, the recovery included not only valuable equipment, but also valuable data. The quick response from JAMSTEC is recognized as a testament to the long collaboration between PMEL and JAMSTEC.

The break occurred under relatively benign conditions in the middle of a continuous section of $\frac{3}{4}$ " nylon, 300 m below the lower terminus of the jacketed wire rope, ~1000 m below the surface. Because of the quick and careful recovery, a thorough engineering analysis of the break could be performed (Lawrence-Slavas et al. 2006). The break did not occur at a splice. The cause of the break is not certain, although, it appears to be most likely due to a manufacture defect in the nylon.

In May 2006, KEO was redeployed as a piggy-back project on the final KESS mooring cruise aboard the R/V Melville with S. Jayne (WHOI) as chief scientist. KESS also supported KEO by providing additional mooring technicians and shipboard equipment. The KEO project is very grateful for the support provided by KESS. The PMEL scientific party included 1 mooring technician (P. A'Hearn) and a TAO programmer (S. Moon). The KEO PI (M. Cronin) traveled to Yokohama Japan to help stage the buoy prior to deployment and to meet with JAMSTEC scientists to discuss the PMEL-JAMSTEC partnership.

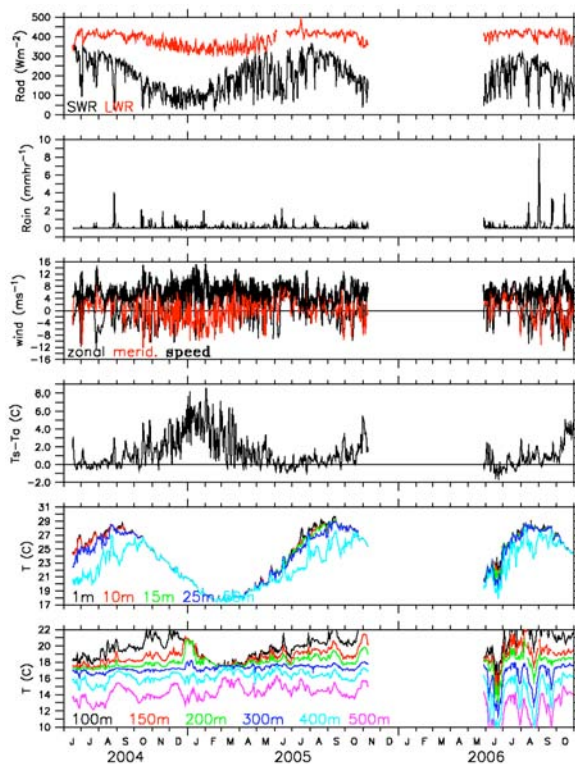


Fig. 3. Select KEO daily-averaged data through October 2006.

Select time series are shown in Fig. 3. The full suite of KEO meteorological measurements include: wind speed and direction from a sonic anemometer, air temperature, relative humidity, rainfall, and solar and longwave radiation. Daily-averages of all met data are telemetered in near-realtime. Surface and subsurface measurements include sea surface temperature and salinity at 1 m (both of which are telemetered), subsurface temperature at 28 depths down to 525m (12 of which are telemetered), subsurface salinity at 15 depths down to 525m (5 of which are telemetered), and pressure at 7 depths (3 of which are telemetered). Thus upper ocean temperature has approximately 25 m depth resolution, subsurface salinity has ~50-75 m resolution, and subsurface pressure (to remap the slackline depths) has 75 m resolution. This resolution is necessary to monitor the mode

water formation when the mixed layer can be more than 400 m deep. Three current meters were also attached at 5 m, 15m, and 35 m (all of which are telemetered) to monitor the near surface currents.

| | FY06 Data Returns | |
|---------------------------------|--------------------------|-----------------------|
| | full year | while in water |
| Meteorological variables | 45% | 100% |
| Upper ocean temperature | 33% | 99% |
| Upper ocean salinity | 30% | 91% |
| Near surface currents | 19% | 42% |

Table 1. KEO data return for FY06 based upon daily-averaged delay-mode data and telemetered daily-averaged data after May 28 2006.

Data returns are reported in Table 1 for the full 365 days of FY06 as well as for the 162 days that the mooring was in the water. Current meters have had a troubling data return, with complete failure of one of the three sensors during each deployment and many data drop outs. The other sensors however had in general excellent data return (when the mooring was in the water). In particular, as with FY04 and FY05, in FY06 the meteorological sensors had 100% data return when the mooring was in the water. This period included the passages of two typhoons: IOKE in August 2005 and YAGI in September 2005. The center of YAGI in particular came within 30 nm of KEO and will be analyzed in great detail. Unfortunately, the third typhoon to pass over KEO (SOULIK on October 17 2006) damaged the relative humidity sensor. We are very grateful to JAMSTEC for helping us make arrangements for this sensor to be repaired in January 2007.

Deliverable 2: Access to KEO data and metadata in a format and through linked webpages to encourage broad use of data.

KEO data are the first PMEL data to be in compliance with the OceanSITES data standard. Daily-averages of nearly all data (surface and subsurface) are telemetered to PMEL and made available in near-realtime from:

<http://www.pmel.noaa.gov/keo/data.html>

Because the KEO array has been an array of one buoy, the data have been withheld from the Global Telecommunications System (GTS) so that they can be used as an independent validation in comparisons with satellite and numerical weather prediction (NWP) fields. With the deployment of the second buoy in the region, this decision will be reviewed. High-resolution surface and subsurface data will be made publicly available through the KEO website within 6-months of recovery. At this point there is no user registry and so we have no way of monitoring the number of data downloads. This will likely be reviewed in FY07.

Deliverable 3: Scientific analyses utilizing KEO data.

KEO data is a critical component of various scientific studies in progress. In particular, the KEO PI (Cronin) and Dr. N. Bond at PMEL/UW JISAO were recently funded to do a set of KEO analyses under a NOAA CLIVAR project titled “Role of Air-Sea Interaction in the Kuroshio Extension Recirculation Gyre”. At the 2006 Ocean Sciences conference, both Cronin and Bond presented results on the upper ocean heat budget for the Kuroshio Extension Recirculation gyre (Cronin et al. 2006) and regional air-sea interactions during KESS (Bond and Cronin 2006a). The analysis of regional weather patterns during periods of anomalous air-sea interaction has subsequently been submitted to the Journal of Climate (Bond and Cronin 2006b).

Large air-sea temperature differences can be seen in the KEO time series (Fig. 3) from October through March. Heat fluxes associated with cold-air outbreaks can contribute to explosive cyclogenesis, yet are often poorly modeled and can contribute to systematic biases in seasonal and climatological NWP flux estimates. However, the summertime radiative heat fluxes appear to also have large biases. Radiative and turbulent air-sea heat fluxes computed from the KEO data are being used for comparisons with the J-OFURO satellite derived flux products (Kubota et al., 2006).

As can be seen in Fig. 4, the Kuroshio Extension appears to have switched from a quasi-stable path-state, to an unstable path state. Periods with quasi-stable path, tend to have larger eastward surface transport, more northern zonal-mean path, and an elongated recirculation gyre; while periods with the unstable path tend to have a weaker eastward surface transport, more southern mean path, a contracted recirculation gyre. The KEO site is well-placed for investigating the processes affecting the recirculation gyre’s heat content and their relationship to the state of the system.

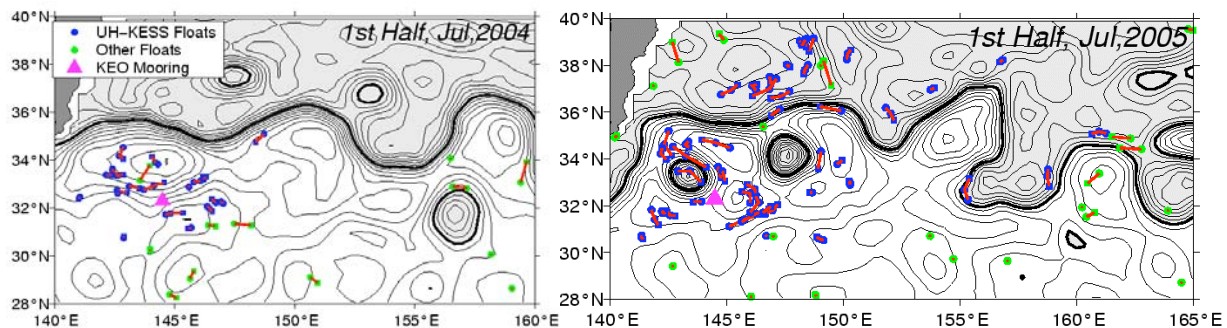


Fig. 4. Sea level height and ARGO float tracks in the Kuroshio Extension region during the first half of July 2004 when the KE was in a quasi-stable state (left) and during the first half of July 2005 after it had become unstable. The KEO site is indicated by a magenta triangle. Sea level height contours can be interpreted as surface geostrophic streamlines of flow.

FY06 Bibliography

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